Renewable and Sustainable Energy Reviews 14 (2010) 2808–2818

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Electricity generation cost in isolated system: The complementarities of natural gas and renewables in the Canary Islands

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ARTICLE INFO

Article history:
Received 12 May 2010
Accepted 10 June 2010

JEL classification:
G32
Q28

Keywords:
Electricity generating cost
Efficiency frontiers
Mean–variance analysis
Isolated electricity systems

ABSTRACT

The Canary Islands offer an example of an isolated electric grid of relative important size within the EU. Due to its peculiarities, the role of renewable energies and their complementarity with fossil fuels offers a solid path to achieving the main energy policy goals of the Islands. The purpose of this paper is to assess the current situation and the energy objectives proposed in the Energy Plan of the Canaries (PECAN, 2006) for the electricity industry, taking into account the average cost and the risk associated with the different alternatives for generating electricity by means of the Mean–Variance Portfolio Theory. Our analysis highlights the inefficiency of the current electricity generating mix in terms of cost, risk and lack of diversification. Shifting toward an efficient system would involve optimizing the use of endogenous energy sources and introducing natural gas to generate electricity. This scenario would mean reducing both cost and risk by almost 30% each, as well as atmospheric CO_2 emissions. Our results agree with the PECAN philosophy.

Contents

1. Introduction

In 2008, the European Union settled on a policy agenda whose purpose was to comply with certain key energy objectives: sustainability, competitiveness and security of supply. To that end, goals were established to reduce greenhouse gas emissions by 20%, to increase the share of renewable energies in primary energy consumption by 20% and to improve energy efficiency by 20% (the 20–20–20 initiative). Along the same lines, Spain's Energy Policy has resulted in various laws and documents.[1] In the Canaries, the basic

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doi:10.1016/j.rser.2010.06.007

[1] Plan de Ahorro y Eficiencia Energética 2004–2012, Plan de Energías Renovables 2011–2020.

document is the *Canaries Energy Plan* 2006 (PECAN, 2006).[2] The set of measures in PECAN 2006 allow the Archipelago energy system to reduce emission levels and its dependence on oil thanks to the introduction of natural gas and an increased reliance on renewable energies, especially solar and wind power, to generate electricity.

The Canaries represent a clear example of an isolated energy system of relative important size within the EU. Isolated grids feature a set of characteristics that usually imply a greater energy dependency and vulnerability, requiring the need for specific planning. Generally, these systems do not have access to every technology available, nor can they be connected to continental grids if necessary. That is why the role of renewable energies and their complementarity with fossil fuels presents a solid path to achieving the main energy policy goals. A study of the electrical system in the Canaries can serve as an example for other similarly sized isolated systems in which the only endogenous energy source is provided by renewable energies.

The aim of this paper is to assess the current situation and the energy policy objectives proposed in PECAN 2006 for the electric industry in the Canaries, taking into account the average cost and the risk associated with the different electricity generation alternatives available. As noted in Awerbuch [1], Awerbuch and Berger [2] and Gross et al. [3], among others, most research on investment and planning decisions in the energy industry is aimed at an individual study of the costs of the various technological options for generating electricity (*stand-alone generating costs*) and on minimizing these costs.[3] This approach, however, relegates to the background two particularly relevant issues. First, not only should the average cost of each alternative be considered, but also the associated risk, measured in terms of uncertain cost fluctuations. Second, the relevant exercise is not the stand-alone analysis, but to jointly analyze all of the technological options of a so-called electricity generating *portfolio* (or *mix*).

Taking into account the average cost and the associated risk simultaneously, the Mean–Variance Portfolio Theory [4–6] offers a useful tool for planning an electrical system from the standpoint of social welfare. This theory has been widely used in finance[4] and subsequently applied to the energy industry.[5] This methodology places special emphasis on the cost interrelationships between the different alternatives (i.e., their cost correlations) and market risk.[6] Thus, this theory is well suited to analyzing isolated systems because it exploits the benefits of diversification between alternative technologies to reduce the risk of the electricity generating portfolio, which is higher in such isolated systems than in an interconnected economy. To the best of our knowledge, this is the first paper to analyze these characteristics within the context of an isolated electrical system.

This paper is structured as follows. In the next section, we analyze the characteristics of isolated electrical systems and describe the situation in the Canaries. In Section 3, we calculate the electricity generating costs (the *bus-bar levelized cost*) of the different technologies considered for the Canaries by means of a probabilistic cost analysis (Monte Carlo experiment). Calculation details are given in the Appendix. In Section 4 we apply the Mean–Variance Portfolio Theory by using the average costs calculated in the previous section in order to estimate efficiency frontiers in terms of average costs and cost uncertainty (risk). The different scenarios are defined based on the risk structure considered[7] (cost variance and covariance) and alternative efficiency frontiers are obtained. Using the frontier for a realistic scenario, we evaluate the current electricity supply situation in the Canaries, as well as the proposal contained in PECAN 2006. The main conclusions are presented in the last section.

2. Electricity generation costs in isolated economies

2.1. Characteristics of isolated electrical systems

Isolated electrical systems exhibit a series of characteristics that contribute to increase the cost and the uncertainty of the electricity generation. Weisser [7,8] examines the main problems facing these types of electrical systems, highlighting the increased cost of the electricity supply in these situations caused by, among other things, high fuel transportation costs resulting from the distance of supply sources and by the absence of endogenous energy sources.

The smaller an electrical system's size, however, the more the largest expenses will be. The production units cannot exceed a certain size since the loss of a group would mean the loss of a high percentage of the entire system. As a result, economies of scale cannot be adequately exploited like they can in large electrical systems, which serve to complicate the technical control of the grid in terms of frequency and voltage. The isolation also requires maintaining a greater reserve capacity to ensure an adequate supply. The greater flexibility offered by interconnected grids is not available in these systems. All of this requires that they be planned and treated differently from continental grids.

Territories belonging to a State normally charge the same rate, meaning that isolated systems, due to the higher supply costs, must be subsidized by the citizenry as a whole, as in Spain. Obviously, in such a situation, regulations play an important inter-territorial redistributive role. Under these conditions, the introduction and development of mainly renewable endogenous energy sources is an important complement to conventional models based on fossil fuels [9]. This complementarity offers a solid tool for achieving the main energy policy goals: economic efficiency, respect for the environment and security and diversification of the supply. And yet, the interruptible and irregular nature of renewable sources, along with the isolation of the economy, can significantly condition the penetration rate of renewables into these electrical systems. So, given the current state of technology in renewable sources, these economies continue to rely on conventional plants as the basis for their electrical systems. Hence, ideally, these plants should be as efficient as possible and be able to provide the greatest guarantee of the security of supply.

2.2. The electrical system in the Canaries

The Canary Islands are extremely dependent on external sources of energy and feature almost no diversification. Comparing the situation with the mainland, we should note that the diversification in the mainland was greatly superior in 2007, with oil and its derivatives providing 50% of the primary energy and renewables 7%, while in the Canaries these sources were 99.13% and 0.87%, respectively. We must keep in mind that the structure of

[2] See Pecan [18] at www.gobcan.es/cicnt/doc/industriayenergia/energia/pecan/pecan.pdf.

[3] Ramos-Real and Afonso [21] and Ramos-Real et al. [22] study the generation costs of fossil technologies in the Canaries. In this paper, we expand that study to a larger number of technologies using updated data. We also conduct a probabilistic study of the costs by means of a Monte Carlo experiment, which allows us to consider the uncertainty inherent in the parameters used to estimate said costs [10].

[4] See Refs. [23–25], among others.

[5] See Refs. [26,2,11,27–30].

[6] As noted in [31], the *market risk* is known as *systematic* risk, and affects all members of a group simultaneously, i.e. the price of the fuel used to generate electricity. See also Ref. [12].

[7] These scenarios are consistent with those typically found in the literature. As we shall see, the most important results are quite robust to the scenario considered. Although the results are not shown, we conducted numerous sensitivity analyses for the scenarios proposed, and the main conclusions reached remain the same.

Table 1
Electricity generation by islands in the Canaries (GWh).

Year	Tenerife	La Palma	Gomera	Hierro	G. Canary	Lanzarote	Fuertev.	Total
1985	794.3	80.71	13.14	6.56	1020.72	149.16	147.59	2112.12
1995	1691.40	149.04	33.23	16.61	2065.04	405.48	258.54	4570.47
2007	3643.85	262.74	67.69	39.72	3666.46	863.65	671.40	9215.50

Source: Department of Industry and Energy, Government of the Canary Islands. Compiled by authors.

primary energy sources in the Canaries is highly conditioned by the production structure of the electricity industry.

The electric industry in the Canaries has the features of an isolated system because it is disconnected from the large European grid. Additionally, each island has an independent electrical grid, with the exception of the connection between Fuerteventura and Lanzarote. Table 1 shows the electricity production in the seven islands and highlights the size and importance of each of the insular electrical subsystems. The two largest islands are comparable with the EU's main isolated systems in terms of installed capacity, demand profile and size and levels of voltage grids. The installed capacities on the islands of Tenerife and Grand Canaria, as well as the peak demands, are similar to those on the island of Crete and somewhat lower than those on Cyprus, both within the EU territory. The Lanzarote–Fuerteventura system size is similar to that on the Caribbean island of Guadeloupe, a French overseas territory. Finally, the consumption of the island archipelago (approximately 2 million inhabitants) is half that of the island of Puerto Rico, with some four million inhabitants, and somewhat greater than those of Jamaica and Trinidad and Tobago, with populations of three million and one million three hundred thousand, respectively.

This fragmentation into small subsystems means that oil derivatives are used almost exclusively as the primary energy source, which also limits the technologies utilized and the size of the generating units. Thus, in 2007, 74% of the primary energy units in the Canaries used fuel oil (in steam, gas and cogeneration turbines), 22.4% used diesel, primarily on the smaller islands, 3% relied on wind and 0.5% on photovoltaics.[8] In comparison to other isolated systems, this extreme reliance on oil is not unusual. In Cyprus and Malta, for example, the reliance on oil is 100%. Trinidad and Tobago rely 100% on natural gas, while Jamaica is 98% dependent on oil.

2.3. Electricity regulation in the Canaries

The regulation of the electrical system in the Canaries features some notable differences with respect to the mainland, of which we note two: first, a greater level of intervention in planning the sector at the generation stage; second, a special tariff and cost compensation system for electric utilities in the islands. These characteristics, along with those competences determined by Spain's legal framework, give rise to the existence of an energy policy that gives local Government in the Canaries an important role in planning the electricity industry.[9]

As a consequence of this energy planning role assumed by the local Government, PECAN 2006 was devised as a reference instrument to be used in electricity planning. The basic principles can be summarized as increasing energy diversity, reducing generation costs, increasing the security and complementing fossil energies with endogenous ones, mainly wind and photovoltaic. The set of measures in PECAN 2006 will allow the energy system in the Canaries to diminish its dependence on oil from the current 99.13% to 72% by 2015. The main initiatives affecting the electrical industry are detailed below:

1. *The rational use of energy*: The goal is to increase overall efficiency in the industry by 25%.
2. *Renewable energies*: PECAN foresees increasing these to reach an 8% of the primary energy sources, which would imply a 30% of electricity generation by 2015. An installed wind capacity for the Canaries of 1025 MW is proposed for 2015, along with 160 MW in photovoltaic energy, also for 2015.
3. *Natural gas*: Natural gas would be used in combined cycle plants (total installed power of 840 MW) on the two largest islands, bringing this source's total of the primary energy balance to 20% by 2015 (5433 Ktep). This amount is equivalent to 40.5% of the net electricity generation in 2015.

3. Probabilistic analysis of electricity generating costs in the Canaries

The purpose of this section is to estimate an average cost for each generating technology. These results will be used in the next section to calculate the electricity generating efficiency frontier for the Canaries in terms of both average cost and risk. Calculating the cost of generating electricity by different technologies is an important factor to decide the optimal generating mix. The most utilized method (*bus-bar levelized cost*) calculates the costs over the electric plants' useful lifetimes and averages them to yield a total production cost. We carry out a probabilistic analysis similar to that used in Feretic and Tomsic [10].

In this section we deal with the general aspects considered in calculating each technology's costs and present an overview of main results. The details of the methodology used in this probabilistic analysis, as well as the specific values for the various parameters used in our calculations, are shown in the Appendix. The generating options considered include the main technologies in use in the Canaries, which are fuel oil, diesel, on-shore wind and photovoltaic (PV) plants. The only feasible alternative in the short term in the Canaries is offered by combined cycle natural gas plants.[10] So as not to bias the comparison with current fuel plants (*fuel-old*) in favor of new combined cycles natural gas plants, we also consider the possibility of using fuel-oil plants (*fuel-new*) that are as efficient as those of natural gas.[11] Fig. 1 shows the estimated frequency histograms of the costs for the six possibilities considered. Table 2 shows the average value and the 5th and 95th percentiles.

[8] We can provide some information based on the Canaries Energy Statistics (2000). The greatest average capacity units are steam turbines from oil, with the largest being the four 80-MW units installed in 1996 on the two biggest islands. Diesel engines are used on every island and are the sole source on La Gomera and El Hierro, these engines being well-suited to small capacity systems, those in the 0.25–5 MW range being predominant on the smaller islands. This indicates that, for example, the average size of the carbon-based generating units on the mainland is greater than the largest units present in the Canaries.

[9] See Pérez and Ramos-Real [9,32] for a detailed discussion of the regulations specific to the industry in the Canaries, following the European guidelines (see [14] and [15]).

[10] Combined cycle plants are currently installed on Tenerife and Grand Canary, though for the time being they are running on diesel.

[11] Nuclear, coal and hydraulic facilities are not considered. Coal has been explicitly excluded from the Canaries' energy policy since the 1990s and nuclear is not deemed feasible given the size of the islands. As for hydroelectricity, there is the possibility of using mini-hydroelectric plants. On the island of La Palma there is even a small plant and one is planned for El Hierro. In this paper, however, for reasons of simplicity and due to a lack of reliable cost data, this technology is not considered.

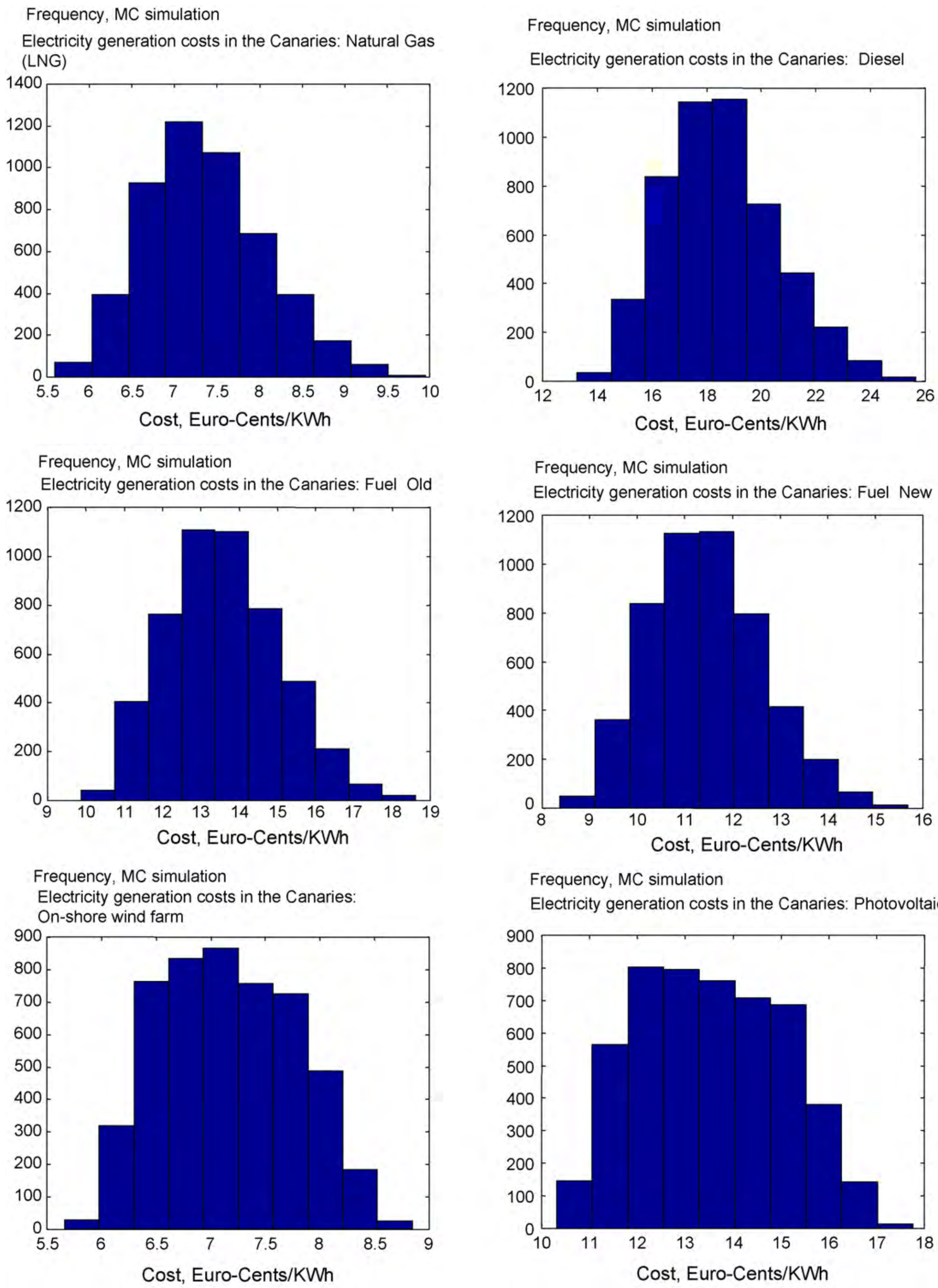


Fig. 1. Histograms for electricity generation costs in the Canaries.

The cheapest generating cost is for the natural gas technology, and is around 7.34 euro-cents/KWh. In terms of the 5th and 95th percentiles, this gives it a 90% probability of being in the 6.27–8.58 euro-cents/KWh range. The range for current fuel-oil plants is between 11.37 and 16.20, the average being slightly over 13 euro-cents/KWh. Note that the 95th percentile for combined cycle gas plants is far below the 5th percentile for current fuel plants. The same is true for the *fuel-new* plants, though their cost would be between 9.6 and 13.6 euro-cents/KWh. The most expensive generating alternative is for diesel plants, whose cost spans from 15.6 to 22.4 euro-cents/KWh, the average cost being 18.59.

As for renewables, wind energy is the only technology in the Canaries whose costs approach those of a combined cycle gas plant. Its cost would range from 6.22 to 8.14 euro-cents/KWh, with an average cost of 7.16. Finally, the generation costs for PV vary between 11 and 16 euro-cents, with the average being 13.5, just below that of diesel plants. We should note that intermittency costs were taken into account for wind power but not for PV, since we assume the PV share will not exceed 10%.[12] PV costs remain

[12] For both technologies, OM costs somewhat higher than those assumed in other papers were used to account for the special climatic conditions in the Canaries stemming from airborne sand, high winds and suspended dust.

Table 2
Electricity generation costs in the Canaries (euro-cents/KWh).[*].

	CC GAS	Diesel	Fuel 'old'	Wind (on-shore)	PV	Fuel 'new'[a]
Average	7.34	18.59	13.57	7.16	13.54	11.48
95th percentile	8.58	22.41	16.20	8.14	15.94	13.61
5th percentile	6.27	15.47	11.37	6.22	11.21	9.61

[*] Probabilistic estimate of levelized bus-bar cost; 5000 Monte Carlo simulations. Costs include market costs of CO_2 emissions and, for wind farms, the intermittency cost.
[a] This technology assumes the same efficiency factor as *CC* diesel or gas plants.

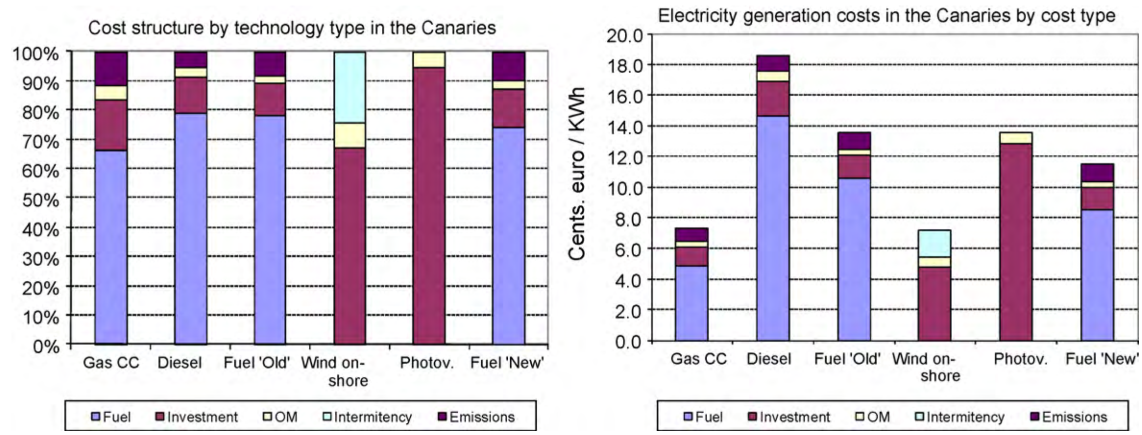


Fig. 2. Electricity generation cost structure in the Canaries.

high, though they have dropped quite significantly in recent decades, and are expected to continue doing so in years to come.

Lastly, we consider the percentage cost structure. Fig. 2 shows the results by type of cost (in euro-cents on the left and percentage of the total on the right). Note how gas plants exhibit costs that are significantly lower than those for diesel and fuel-oil plants in every category (including emissions). Also, the cost structure for fossil fuel plants differs considerably from that for renewable energy plants. In the former, fuel accounts for a majority of the cost, while in the latter, it is the capital cost that is the most significant component. Also, emission costs are non-existent for renewables and significant for fossil plants, especially those based on fuel oil and diesel.[13]

4. A mean–variance portfolios analysis

In this section we apply the Mean–Variance Portfolio Theory to calculate the efficiency frontier for the electricity system in the Canaries in terms of both average cost and risk. Our analysis is based on the cost calculations made in the previous section. We assume alternative risk scenarios and choose one as a reference for evaluating the relative efficiency of any given energy portfolio proposed with respect to the estimated frontier. Each point I the frontier minimizes electricity generation costs for any given feasible risk factor and any technological restrictions that may be specified. Thus, our analysis adopts the perspective of maximizing social welfare, as noted by Awerbuch and Berger [2] and used in the mainstream literature.[14]

Since this work is specifically tailored to the Canaries, we describe the methodology without focusing on technical aspects.[15]

We start by explaining the most important factors in measuring the risk of an energy portfolio, and illustrate with a graphical example the most salient aspects of an electricity generating efficient frontier. We then define different risk scenarios that provide various efficiency frontier estimates. Lastly, we evaluate the current situation in the Canaries and the proposals in PECAN 2006 using the scenario that we believe to be the most realistic.

4.1. The generating electricity efficiency frontier

An electricity generating portfolio is represented by the set of all the weights of the different electricity generating technologies. In our case, X_1 is the percentage supplied by *CC* gas plants, X_2 by diesel, X_3 by 'old-fuel' oil plants, X_4 by on-shore wind, X_5 by PV and X_6 by 'new fuel' oil plants. These weights must always add up to unity and are subject to certain technical restrictions. While the weights X_1, X_3 and X_6 could range, in principle, from zero to one, X_2 has a lower limit of 0.15 due to the need to use these plants on small islands, while those for wind and PV have upper limits of 0.30 and 0.10, respectively, to ensure the security and stability of the electricity supply due to the isolation of the electricity grids on the islands and the problem of intermittency of these technologies.[16] Given these weights, the average price of the energy portfolio is defined as the weighted average of the various individual costs:

$$\overline{CC} = X_1 \cdot \overline{C_1} + X_2 \cdot \overline{C_2} + X_3 \cdot \overline{C_3} + X_4 \cdot \overline{C_4} + X_5 \cdot \overline{C_5} + X_6 \cdot \overline{C_6}$$

Based on the above average cost analysis, the greater the weights of natural gas and wind, the lower the cost of the energy portfolio.

The year-to-year variance (or its squared root, i.e., the standard deviation) of historical data is the usual way of measuring risk.[17] In

[13] In this paper we do not consider the total life cycle emissions costs of each technology, such as, for example, those involved in manufacturing and scrapping photovoltaic panels, wind turbines or other aspects related to environmental impact. A rigorous study of these aspects require an analysis that is beyond the scope of this article.

[14] In liberalized markets, the objective function is different, as portfolios are chosen to maximize financial returns to investing generators [30].

[15] For a more detailed description specifically applicable to the case of electricity generation, we recommend Awerbuch and Berger [2] or Awerbuch and Yang [11].

[16] Although a maximum of 30% by 2015 is specified for wind and solar in PECAN 2006, there is already talk in the Government of the Canaries of 40% between both technologies in the longer term.

[17] There is a considerable literature on risk measurements. Despite the criticism of using the standard deviation as a measure of risk, it is still the most widely used. Most cases in the related literature use the standard deviation as a measure of risk. An in-depth analysis of how to measure risk in energy portfolios is an interesting extension of the methodology presented here, but is beyond the scope of this work.

the case of a specific generation technology, the risk would be ideally calculated by using a measure of the dispersion of its costs. This cost dispersion depends on many factors, such as the variability in the fuel price,[18] in the OM cost, the uncertainty during the construction period (the investment risk), in the price of CO_2 emissions, the risks associated with its regulation, and on all of its cross-correlations. But the important risk is the one related to the electricity generating mix. So as to better understand the variance expression (the measure of volatility used) for the mix, let us assume only two technologies, *A* (i.e., gas) and *B* (i.e., PV):

$$Var(mix) = X_A^2 \cdot Var(C_A) + X_B^2 \cdot Var(C_B) + 2 \cdot X_A \cdot X_B \cdot cov(C_A, C_B)$$

Though this is a well-known expression, it is highly illustrative. The estimating risk of an electricity generating portfolio depends on individual variances weighted by the square of their weights, but it also depends on how their costs evolve together (their cost covariance matrix). Thus, the lower the correlation between the costs of *A* and *B*, the lower the variance and risk of the energy portfolio. Note, for example, that if the covariance is highly negative (associated with a correlation close to −1), the variance of the energy mix could be almost negligible. See Awerbuch and Berger [2], Awerbuch and Yang [11] and Roques et al. [30] for a detailed discussion of this topic.

Unfortunately, unlike with financial assets, it is unrealistic to assume negative correlations among the costs of different electricity generating technologies. Instead, the correlations among the technologies involved can be very high, especially among those derived from fossil fuels – around 1 for fuel oil and diesel and somewhat less between gas and the first two. There are other technologies with low cost correlations, in which case we could speak of *complementary* technologies. Hence, combining complementary technologies would lower the risk of the energy portfolio, even for technologies with similar and high individual risk values. This last aspect is extremely important to the proper design of a national or regional energy policy, and can only be analyzed when looking at the whole portfolio.

Once the average cost and risk of an electricity generating portfolio is determined, an efficient mix is defined by a set of weights for the various technologies considered that, for a given level of risk (i.e., variance or its standard deviation), will minimize the average cost for every feasible combination, given technical restrictions. The set of all efficient portfolios comprise what is known as the *efficient frontier*.[19]

Fig. 3 shows one possible efficient frontier. The average cost is along the *y*-axis, and the measure of risk along the *x*-axis. The minimum cost (MC) mix includes the cheapest technologies. Starting from this mix, if we move left along the frontier, more diversified portfolios would presumably increase the average cost while simultaneously reducing the variance until what is known as the minimum variance (MV) mix is reached. Being to the left of the frontier is unfeasible, given the technologies involved and the restrictions assumed, while any portfolio above the MV or to the right of the frontier will be inefficient.

The estimated frontier allows us to assess specific portfolios and offer suggestions for improvement. Suppose, for example, that we wish to assess portfolio *A*, which is inefficient. We can define two portfolios of particular interest with respect to *A*. One is a portfolio with the same risk as the initial one (*B*), which involves the same risk but a lower cost by virtue of being close to the frontier. The other portfolio has the same cost as the initial one (*C*), and involves

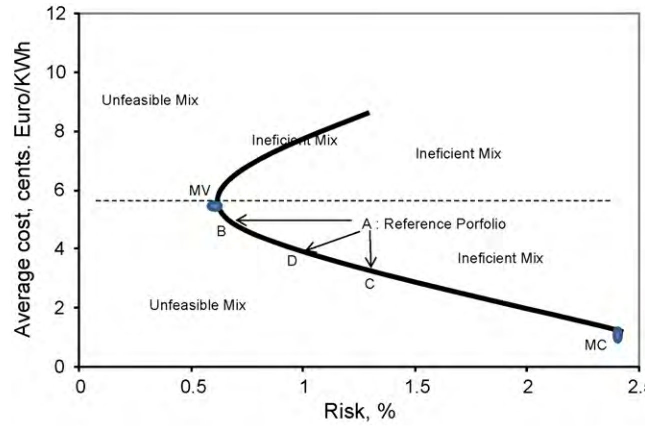


Fig. 3. An example of an electricity generating efficient frontier.

moving closer to the frontier, reducing risk. In reality, any mix between portfolio *B* and *C* will be more efficient than the reference mix, since it will prevail in both dimensions (average cost and risk).

4.2. Defining different risk scenarios

In this section we first describe reasonable scenarios for the risk structures of the alternative technologies considered. Next, for these scenarios, we estimate their corresponding efficient frontiers. The lack of historical data for the different type of costs (fuel, investment, OM, etc.) and, in the case of regulation, of their qualitative nature, makes it very difficult to obtain a reliable quantitative estimate for individual risks as well as of their correlations. We will not go into details on the precise calculation of individual and the mix portfolio risk, which goes beyond the scope of this paper. Instead, and based on the existing literature, we will use reasonable scenarios for the individual risks and their correlations and perform some sensitivity analysis to check the robustness of our results.[20] The different scenarios considered are summarized in Table 3. These scenarios are consistent with those assumed in the literature and with existing evidence.

In our first scenario, denoted S1, we only consider the risk associated with fluctuations in fuel price, meaning that technologies that use fossil fuels exhibit a positive risk, while a negligible risk is assumed for renewables. This is a common assumption made in the literature.[21] In order to have a point of reference for fossil technology risks, we calculate the standard deviation of the trend-adjusted international raw material prices (for oil and for natural gas). Fig. 4 shows the annual series for oil and natural gas prices between 1984 and 2008.[22] The standard deviation of the trend-adjusted price series is 1.29 for oil and 0.95 for natural gas. The correlation is high at 0.87.[23] We assume that diesel and fuel oil generating plants share the same risk, as determined by the price of oil. As for natural gas, its volatility is measured by the dispersion in its import price on the international markets. The correlation between the diesel and fuel oil technologies is assumed to be 0.99.

[18] Although both risks are related [33], in this paper we refer to the fuel price risk that results in a uncertain cost to generate electricity, and not to the fuel supply risk resulting in the inability to generate electricity [31].

[19] The calculations were made using the 'frontier.m' function of the Matlab financial toolbox.

[20] The relevant literature has proposed the use of a volatility measure for observed time series as proxies for quantifying the risk of the different types of costs [2,11] and the use of simulation techniques to estimate the correlations (Roques et al., 2009).

[21] The justification is that the risk that matters most to companies and to societies is the so-called systematic, or market, risk, the most important being that related to the trend in international fuel prices. Moreover, the cost of fuel represents a very high percentage (see Fig. 2) of the total cost of fossil fuel technologies. Finally, as noted in Awerbuch and Berger [2] and Roques et al. [30], the qualitative results do not vary significantly when a more complex risk structure is considered.

[22] The data were taken from the BP annual statistical report for 2009.

[23] We used the Hodrick and Prescott (HP) filter applied to annual series to estimate the trend-adjusted series.

Table 3
Alternative risk scenarios.

	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)	Scenario 4 (S4)
Std. fuel, diesel	1.29	1.29	1.29	1.29
Std. gas *CC*	0.95	1.29	1.29	1.29
Std. renew.	0.0	0.0	1.29	0.65
Corr. (fuel, diesel)	0.99	0.99	0.99	0.95
Corr. (fuel or diesel, gas)	0.87	0.87	0.87	0.87
Corr. (renew1., renew2.)	0.0	0.0	0.0	0.50
Corr. (non-renew., renew.)	0.0	0.0	0.0	0.25

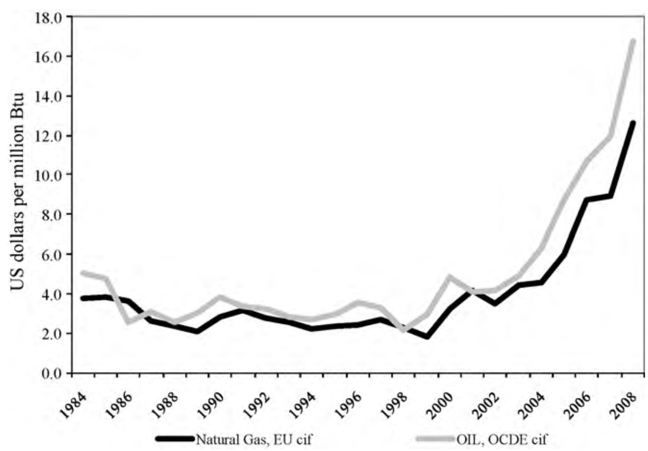


Fig. 4. Raw material prices: natural gas and oil.

Moreover, the cost correlation between renewables and fossil fuels, and among renewables themselves, is assumed to be zero in this first scenario.

In the second scenario (S2), we assume that the price of Natural Gas in international markets is as volatile as that of oil.[24] In this scenario, the standard deviation for the three fossil fuels is assumed to be 1.29, while the correlations and other assumptions remain the same as in S1. In the third scenario (S3), the same risk is assumed for renewables as for fossil fuels. The risk for renewables stems mainly from the uncertainty of investment costs (construction risk) and regulatory risks.[25] The zero correlation between renewables and non-renewables is maintained, as is the high correlation between the various fossil fuels. The goal in considering this scenario is to measure how renewable deployment can reduce the portfolio risk, even if risk of renewables are as high as that for fossil technologies.

Lastly, we present a fourth scenario (S4), which we call *eclectic*. It may be viewed as an intermediate, and more realistic, situation based on the previous scenarios. In S4, the individual volatility among the fossil technologies is the same (1.29); the volatility for renewables is positive but lower (0.65, approximately half); the cost correlation among fossil fuels is 0.95 between diesel and fuel oil, and somewhat lower when compared to gas (0.87); the correlation between renewables is positive, but smaller (0.5); finally, the correlation between fossil fuels and renewables is also positive, but the smallest of all (0.25). The minor sensitivity analyses conducted for this scenario did not yield any significant changes in the results.

[24] Historically, the price of pipelined gas (75% of the total) has been directly linked to oil price trends, though its own price has been more stable. In the medium-term, however, Liquefied Natural Gas (LNG) is going to play an important role in every OECD regional market [34]. In a negative scenario, the price of gas could mirror that of oil, despite of liberalization of gas international trade.

[25] As Wiser et al. [31] points out, this risk represents the possibility that regulatory review or contract renegotiations will alter the benefit or burdens of a contract.

Table 4
Minimum variance (MV) portfolio for different scenarios.

	S1	S2	S3	S4	Average
Cost (euro-cents/KWh)	9.595	10.434	10.466	10.996	10.373
Risk	0.602	0.760	0.889	0.824	0.769
Weight of gas	0.450	0.295	0.276	0.248	0.317
Weight of diesel	0.150	0.166	0.150	0.211	0.169
Weight of fuel oil	0.000	0.042	0.076	0.065	0.046
Weight of wind	0.300	0.300	0.300	0.300	0.300
Weight of solar	0.100	0.100	0.100	0.100	0.100
Weight of fuel oil (new)	0.000	0.097	0.098	0.076	0.068

Table 5
Average portfolio between MV and MC for different scenarios.

	E1	E2	E3	E4	Average
Cost (euro-cents/KWh)	9.283	9.704	9.718	9.983	9.672
Risk	0.649	0.765	0.894	0.827	0.784
Weight of gas	0.500	0.423	0.419	0.356	0.424
Weight of diesel	0.150	0.150	0.150	0.150	0.150
Weight of fuel oil	0.000	0.000	0.000	0.000	0.000
Weight of wind	0.300	0.300	0.300	0.300	0.300
Weight of PV	0.050	0.100	0.100	0.100	0.087
Weight of fuel oil (new)	0.000	0.027	0.031	0.095	0.038

Tables 4 and 5 show the results for the MV portfolio and the average between MV and MC for the four scenarios considered. In the last column, we show, for illustrative purposes, the average of the four scenarios considered. The tables contain the resulting weights for each technology, the average cost and the risk for the various portfolios.

If we focus on the MV portfolio, we note that in every scenario natural gas attains a significant weight (never less than 25%), while renewables take on the maximum technical weight allowed. Diesel, for its part, always remains close to the minimum required to supply the small islands. The largest differences are evident in fuel oil and gas. Fuel oil disappears in S1, while in the other scenarios it represents around 15%, especially due to fuel oil (new). Gas also goes from a weight of 45% in S1 to values of around 30% in the other scenarios. In S1, the low risk technologies are clearly prominent, with gas excelling among the fossil fuels. In the other scenarios, the risk of gas is level with that of other fossil fuels and the mix is somewhat more even. Also of note is the fact that the results for S2 and S3 are almost equal. This indicates that, despite the greater individual risk assumed for renewables in S3, since the correlation with fossil fuels is zero, the introduction of these technologies remains essential to reducing risk in the whole portfolio.

The MC portfolio is the same in every scenario since it does not depend on the shape of the cost variance–covariance matrix. It relies on the cheapest technologies while adhering to the technical restrictions. The weight of gas rises to 55%, fuel oil and photovoltaics are eliminated, diesel is left at the minimum of 15% and wind power is raised to the maximum of 30%. For the average cost levels utilized, the cost of generating electricity for this mix would be 8.97 euro-cents/KWh.

The average portfolio between MC and MV is interesting since, in comparison to an inefficient portfolio, it might win in terms of both average cost and risk. As is the case with MV, if we omit the first scenario, which always favors gas (in this case its weight is 50%), the resulting energy mixes are similar. Of note are the results under S4: 35.6% gas, 15% diesel, 30% wind, photovoltaics also at the technical minimum (10%) and 9.5% for new generation fuel oil plants.

The results for the different scenarios do not vary excessively, except for S1, which exhibits a few peculiarities. Also, note that the result averages (the last column in the tables) are quite similar to the results for scenario S4. Lastly, we note that every scenario

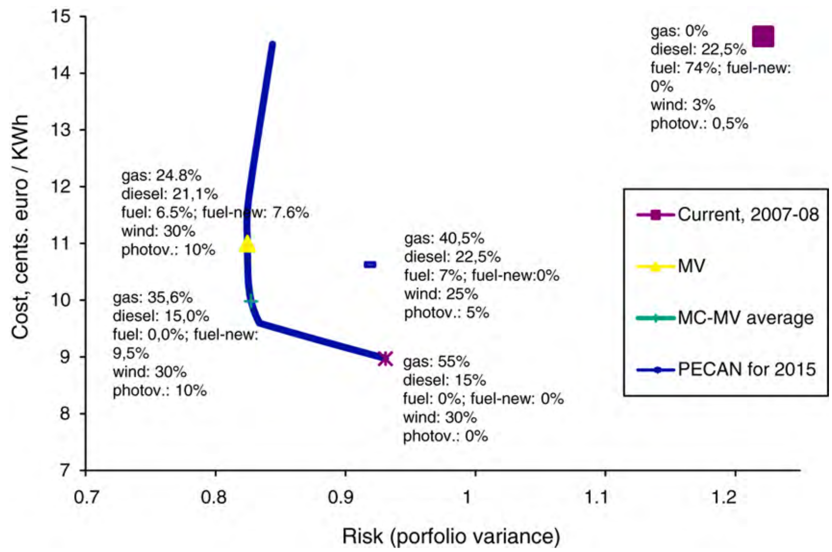


Fig. 5. Efficient electricity generating frontier in the Canaries.

implies a much more diversified energy mix than is currently in use in the Canaries. We will therefore use the frontier estimated for scenario S4 to assess the current energy portfolio in the Canaries, as well as the PECAN goals.

4.3. The efficient frontier: an assessment of the current situation in the Canaries and of the PECAN proposal

The basis for the electricity generation portfolio in the Canaries assumes the following weights: 0% natural gas, 22.5% diesel, 74% × oil, 3% wind and 0.5% solar. The average cost of this portfolio is 14.51 euro-cents/KWh. Fig. 5 shows the estimated energy frontier under scenario S4, along with this initial portfolio, the MC, the MV and the average of the two. Table 6 shows the scenario S4 results for all of these portfolios.

The first item of interest is the extreme inefficiency of the current mix in the Canaries, which is far from the frontier in both directions. It is so much so that the portfolio with the same cost of the initial (portfolio *B* in Fig. 3) is also not efficient, since it would be above the MV mix. As for the portfolio with the same risk as the initial (portfolio *C* in Fig. 3), given the estimated frontier, it would not be defined for the current mix in the Canaries, since there is no portfolio within the efficient frontier that exhibits such a high risk. The nearest case to this theoretical portfolio would be the MC mix. That is why we use the average portfolio between MC and MV to evaluate the current portfolio in the Canaries as the reference portfolio.

With respect to the average cost of the current mix in the Canaries, the MV mix would reduce it by over 3 euro-cents/KWh (24.4% less) and by almost 5.5 if compared to the MC (38.2% less). Its risk is almost 50% greater than that of the MV and a little over 20% with respect to MC. This is explained by the high weights of fuel and diesel (the most expensive, volatile and highest correlation sources). Shifting to the MV portfolio would result in a much greater diversification from among the fossil fuel mixes, with gas as the main source, and especially in a large degree of complementarity (in actuality, the maximum possible) with renewables. Shifting to the MC mix, on the other hand, would mean focusing everything on natural gas and wind and keeping a bare minimum for diesel (55% gas, 15% diesel and 30% wind). The average portfolio (MV–MC) represents a 31.2% drop in the average cost and a 32% drop in risk. This portfolio, as commented previously, diversifies the utilization of the various technologies with respect to the MC portfolio. We recall its weights: 35.6% gas, 15% diesel, 9.5% ‘new’ fuel oil, 30% wind and 10% PV.

The portfolio proposed in PECAN 2006 assumes the following weights: 40.5% gas, 22.5% diesel, 7% old fuel oil, 25% wind and 5% solar. We note that, though it also is inefficient, it is much closer to efficiency than the current mix. The PECAN, then, may be said to be a step in the right direction. With the PECAN portfolio as a reference, we can calculate the PSCI and PSRI, though we should note that they are very similar to the MC and MV portfolios, respectively. Thus, we also use the average MC–MV portfolio as the reference mix in this case.

Based on this comparison, with respect to the portfolio proposed in PECAN, the cost could be reduced by an additional 5.5%, and the risk almost 10%. Of particular importance in the comparison is the convenience of reducing the weight of diesel (by over seven points, to 15%), eliminating the old fuel oil plants and having more efficient plants that use this fuel, reducing the weight of gas by almost four percentage points (though it would continue having the highest weight, above 35%) and, above all, promoting the greatest possible use of renewables, both wind and solar.

Table 6
Assessment of Canaries and PECAN electricity generating portfolios.

	Electricity portfolio in the Canaries 2007–08	Electricity portfolio proposed in PECAN 2015	MV portfolio	MC portfolio	MV–MC average portfolio
Cost (euro-cents/KWh)	14.511	10.572	10.996	8.970	9.983
Risk	1.217	0.918	0.824	0.931	0.827
Weight of gas	0.000	0.405	0.248	0.550	0.356
Weight of diesel	0.225	0.225	0.211	0.150	0.150
Weight of fuel oil	0.740	0.070	0.065	0.000	0.000
Weight of wind	0.030	0.250	0.300	0.300	0.300
Weight of PV	0.005	0.050	0.100	0.000	0.100
Weight of fuel oil (new)	0.000	0.000	0.076	0.000	0.095

To achieve the objectives laid out in PECAN 2006, and even more so those specified in our efficiency proposal (MC–MV average), the endogenous energy sources need to the exploited to the maximum. Achieving the latter would result in a significant reduction in both cost and risk, on the order of 32%, as well as in atmospheric CO_2 emissions,[26] which would contribute to the general goals of protecting the environment and limiting climate change.

In both scenarios, the situation for the electrical system in the Canaries would mean that diesel would be restricted to the five smaller islands, which would also be supplied by renewable energies and, on the islands of Fuerteventura and Lanzarote, by new fuel oil plants. Gas, on the other hand, would form the basis for the supply on the two largest islands which, along with small diesel and/or new fuel oil plants, would be complemented by renewable energies.

The measures we propose would, in practice, mean few modifications to the original goals of PECAN 2006, though their implementation would require additional infrastructure. For example, increasing the weight of renewables by almost 10% would require investing in the grid in order to be able to make use of this energy. Storage systems might also be necessary to compensate for the intermittent nature of these sources. Likewise, the construction of regasification plants on the largest islands is a key and pressing factor if the goal of introducing natural gas is to be achieved.

5. Final remarks and energy policy implications

The objective of this paper is to evaluate the current situation and the energy policy goals proposed in PECAN 2006 for the electricity system in the Canaries. This exercise is submitted as an empirical application in isolated electrical systems in which the complementarity between fossil and renewable energies offers a solid path to achieving the main energy policy objectives. Keeping in mind both the average electricity generation costs and the risk, we used the Mean–Variance Portfolio Theory in our analysis. This theory has been widely used in finance and in the energy sector and is quite well suited to the study of isolated systems, given the emphasis it places on energy diversification and on the risk associated with the various technologies. To the best of our knowledge, this paper presents the first analysis of its kind for the situation in Spain, as well as within the context of an isolated electrical system. The main conclusions drawn from this paper can be summarized in the following points:

1. For the Canaries, the cost of generating electricity from natural gas is the most inexpensive, with wind technology being the only one whose costs are similar to those of combined cycle gas plants.
2. The current energy portfolio for the electrical sector is very inefficient in terms of cost and its lack of diversification. Any risk scenario used as a reference indicates that in order to reduce the overall risk, there must be a shift toward energy portfolios that are much more diversified than today's.
3. Achieving the PECAN 2006 goals and, more significantly, those indicated in our efficiency proposal, requires the maximum exploitation of endogenous energy sources and the introduction of natural gas. This situation would allow for significant reductions in not only cost and risk, but also in CO_2 emissions.
4. The measures proposed would, in practice, require very few modifications to the original PECAN 2006 goals, though additional infrastructure would be necessary to implement them. For example, additional investment in the grid as well as the construction of regasification plants would be essential components in any plan to introduce natural gas.
5. The results of this empirical application serve to highlight the important role played by renewable energies in reducing risks in an energy mix since, despite assuming a risk for renewables similar to that of fossil energies, these sources remain fundamental to reducing an energy portfolio's overall risk.
6. The complementarity between fossil energies (and natural gas in particular) and renewable energies is a relevant factor for the energy policy of an isolated system where few supply options exist, since it is the only way to reduce dependence, increase diversification and lower greenhouse gas emissions.

Acknowledgments

We gratefully acknowledge the comments made by Edmar Fagundes de Almeida, Miguel Becerra, Juan Márquez, José Manuel Guirao and Suisa Da Silva. The authors thank financial support of Focus-Abengoa Research Program on Energy and Climate Change, Canaries Agency program PI2007/025, the coorperation program PHB2007-0022PC (Ministerio de Educación, Spain) and especially of the research agreement between the University of La Laguna Foundation and GASCAN. Marrero thanks also the research program of Ministerio de Ciencia e Innovación (ECO2009-10398).

Appendix A

This appendix summarizes the most relevant aspects for calculating electricity generation costs in the Canaries. We use *CC* to denote the present value for the levelized bus-bar cost in Eq. (A.1), which measures the current value of the cost flows generated over the life of the plant (C_t for each time period t), divided by the current value of the plant's energy output (X_t, for each time period t).

$$CC = \frac{\sum_{t=1}^{N}(1/(1+r)^t)C_t}{\sum_{t=1}^{N}(1/(1+r)^t)X_t} \tag{A.1}$$

where r is the discount factor applied and N is the lifetime of the plant in years. The relevant generating costs can be divided into:[27] investment costs (*IC*), which include the total planning and execution costs and the associated opportunity cost; production costs, which basically include the fuel cost (*FC*) and operation and maintenance costs (*OMC*), which may be fixed or variable; other significant costs, such as emissions costs (imputed to fossil technologies) and interruption costs, which are imputed to renewables with a sizable market share (greater than approximately 15%). These costs are estimated by using the relationship that exists between them and a set of key parameters for which data are available and whose values depend on the technology and on other conditions specific to each particular case (see IEA [20] for more details on this point).

In terms of investment costs, we assume that the investment is made over T periods prior to the start-up of the plant. Let us define the weights Wk, $k = 1, 2, \ldots, T$, as the percentages associated with each plant construction period. Thus, to account for the total construction cost, *ic* (overnight investment cost), in US$/MW of a plant that takes T

[26] Approximately 30% of total emissions in the Canaries by 2015.

[27] This classification is typically used by the International Energy Agency [19], The Royal Academy of Engineering [35] and the UK Department of Trade and Industry [13] and MIT [17], among others, for comparing fossil (primarily gas and coal) and nuclear energy costs.

Table A.1
Parameters for calculating electricity generating costs in the Canaries.

Technology	Useful life	Const. time frame	Construction schedule (% per year)	Investment cost US$ /kW (overnight)	Fuel Price US$/JG	OM Costs US$/kW	Fuel cost growth rate (% annual)	Capacity factor	Efficiency factor	Ton. CO_2 per MWh
Natural gas (LNG)	25–30	3	18–70–12	1100–1300	5.0–6.0 (+0.5 regasification)	30–40	0–3	80–85	52–56	0.40–0.45
Fuel oil	25–30	3	18–70–12	1400–1500	11.0–11.6	25–35	0–3	80–85	46–49	0.55–0.60
Diesel	25–30	3	18–70–12	2150–2250	18.5–20.5	50–60	0–3	80–85	49–51	0.50–0.55
Wind	20–25	1–2	50–50	1700–1800	–	20–25	–	30–35	–	–
Photovoltaic	20–25	1	100	4000–4200	–	30–35	–	25–30	–	–

General assumptions: price ton CO_2 5–20 euros/MWh; wind interruption costs 15–20 euros/MWh.

years to build in today's value, we have:

$$ic \cdot \sum_{k=1}^{T} W_k \cdot (1+r)^{T-(k-1)} \tag{A.2}$$

This term must be equal to the current value of a constant annuity comprising both the annual investment cost, *I*, and the corresponding interest payment.

$$\begin{aligned} ic \cdot \sum_{k=1}^{T} W_k \cdot (1+r)^{T-(k-1)} &= \frac{I(1+r)}{(1+r)} + \frac{I(1+r)}{(1+r)^2} + \ldots + \frac{I(1+r)}{(1+r)^n} \\ &= \frac{I(1+r)}{r}\frac{(1+r)^n-1}{(1+r)^n} \Leftrightarrow I \\ &= \frac{ic \cdot r \cdot (1+r)^{n-1}}{(1+r)^n-1}\sum_{k=1}^{T} W_k \\ &\quad \cdot (1+r)^{T-(k-1)} \end{aligned} \tag{A.3}$$

Finally, this expression is divided by the amount of KWh generated per year, which is obtained by multiplying the number of hours in a year, 8760, by the plant's load or capacity factor (*lf*),

$$IC = \frac{I}{8760 \cdot lf} \tag{A.4}$$

The fuel cost (*FC*) is calculated using the expression

$$\begin{aligned} FC &= \frac{fc\sum_{n=1}^{N}(1+fg)^n/(1+r)^n lf \cdot 8760}{\eta\sum_{n=1}^{N} lf \cdot 8760/(1+r)^n} \\ &= \frac{fc}{\eta}\frac{\sum_{n=1}^{N}(1+fg)^n/(1+r)^n}{\eta\sum_{n=1}^{N}1/(1+r)^n} \end{aligned} \tag{A.5}$$

where *fc* is the import fuel cost as a production input (US$/GJ) and includes transportation, regasification, refining, and other import costs, *fg* is the annual growth rate of *fc* over the life of the plant, between [0,1], and η is the plant's efficiency factor, also between [0,1].

Lastly, we calculate the operating and maintenance costs (fixed and variable):

$$\begin{aligned} OMC &= \frac{omc \cdot \sum_{n=1}^{N}(1+omcg)^n/(1+r)^n lf \cdot 8760}{\sum_{n=1}^{N} lf \cdot 8760/(1+r)^n} \\ &= omc\frac{\sum_{n=1}^{N}(1+omcg)^n/(1+r)^n}{\sum_{n=1}^{N}1/(1+r)^n} \end{aligned}$$

where *omc* is the OM costs as a production input (US$/MW) and *omcg* is the annual growth rate of *omc* over the life of the plant, between [0,1]. The interruption and CO_2 emissions costs may be viewed as a component of OM cost.

The information available on these parameters is not known with any certainty. Based on data obtained from the IEA [19,20], the RAE [35], Spain's Ministry of Industry and conversations with experts on the matter in the Canaries energy sector, we assumed a range of values and probability distributions (generally uniform or triangular, as is the norm) for each parameter and technology to be analyzed in the case of the Canaries. This information is summarized in Table A.1. Given these distributions, a Monte Carlo experiment was then conducted, which consisted of selecting random values for the parameters in the distributions under consideration, calculating the value of the costs, and repeating this process a large number of times (5000 in our case). Thus, instead of finding an average cost value, we obtain a cost probability distribution. This is similar to the process used in Feretic and Tomsic [10].

What follows is a very brief comment on the parameter values (see Table A.1). The overnight investment cost is the total investment outlay (mainly construction and planning costs) expressed as a current value per KW constructed. For the PV technology, this cost is by far the highest, followed by diesel plants, on-shore wind, fuel oil and, with the lowest cost, combined cycle natural gas plants. The load factor accounts for one of the main differences between fossil fuel plants with respect to renewables. This parameter for the former is about 80% in the Canaries (on the mainland and in the rest of Europe, it is 85% on average), while the capacities of the latter are between 25% and 30% on average. The other data required to calculate the investment cost is the time to build the plants (which ranges from one year for a PV plant and three years for fossil plants) and the discount factor, the standard value for which ranges from 5% to 10% for all plant types.

As for the parameters affecting the fuel cost (also expressed in euro-cents/KWh), in addition to the plant lifetime, load factor and discount factor, there are three key parameters. First, and most important, is the actual cost to acquire the fuel. The cost of diesel is clearly the highest, followed by that of fuel oil, with natural being most economical, despite the regasification costs. The fuel cost for the renewable technologies considered is zero. As for the expected fuel acquisition growth rate over the useful lifetime of the plant, we assumed an annual range of 0–3% for the three fuel types considered. The fuel efficiency factor differs among the fossil technologies: the most efficient is for combined cycle gas plants (and the hypothetical new fuel-oil plants), followed by diesel and, lagging far behind, the old fuel-oil plants.

Let us now consider OM costs (fixed and variables costs being expressed in terms of KWh). Diesel plants are the most expensive, followed by fuel and gas. These costs are lower for renewables, though in the Canaries, climate aspects (airborne sand, suspended dust, etc.) result in higher OM costs than in other places, which brings them closer to those of fossil energy plants.

Lastly, we have CO_2 emissions costs, which attempt to internalize the social costs of emissions within the private costs. This cost is calculated as the price of the tons emitted multiplied by the emissions factor resulting from the generation (Tm CO_2/KWh). The first is

common to all technologies and is determined by the emissions markets at the European level. In late 2009 its price was between 15 and 20 euros/TM of CO_2 (this cost is expected to rise above current levels). The emissions factor is zero for renewables and is between 0.40 tons CO_2/MWh for natural gas, 0.55–0.60 for fuel oil and 0.50–0.55 for diesel. Lastly, the interruption cost is only considered for wind, since it is the only renewable technology that is expected to have a penetration rate above 15% in coming years (see [16] for more details about intermittency costs). This cost is estimated at 15–20 euros/MWh [20].

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